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Durability performance of concrete containing condensed silica fume

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Abstract

The paper describes a short-term study carried out to examine the durability performance of various condensed silica fume (CSF) concretes in comparison to portland cement (PC) and PC/ground granulated blast furnace slag (GGBS) controls up to the age of 28 days. Mix proportions were designed to provide 28-day strengths of 30, 40, and 50 MPa for the PC controls and these were used for all binder combinations considered. Concrete durability was inferred from a suite of durability index tests designed to measure concrete resistance to gas, liquid, and ion transport mechanisms. It is shown that concrete durability is dramatically improved through the use of CSF. Optimum performance was achieved through the use of CSF as a 10% addition by mass to the initial binder content. The work also confirms CSF's effectiveness when used in ternary binder blends with PC and GGBS, with these mixes out-performing the controls and selected binary-blended PC/CSF mixes. ©1999 Elsevier Science Ltd. All rights reserved.

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Achieving adequate levels of concrete durability in order to improve the performance and reduce the life cycle costs of concrete structures continues to be a serious problem facing engineers. Benefits, in terms of concrete durability, of using additional binder materials are well established [1–3] and the use of materials such as condensed silica fume (CSF) and ground granulated blast furnace slag (GGBS) are now considered commonplace. While GGBS has been in use in the concrete industry in South Africa for about four decades, CSF has been available commercially only in the last 10 years. During this time its local use has been limited, with approximately two-thirds of that produced annually (about 10 thousand tonnes) being exported. This trend is mainly due to a lack of locally published information on the material and a general low awareness of the necessity of producing durable concrete.

Against this background, a project has been undertaken at the University of Cape Town to quantify the performance of concrete containing CSF. This paper reports work carried out to explore relative concrete durability performance. CSF was used in various binder combinations both as a replacement for, and direct addition to, portland cement (PC). In addition, a series of mixes where CSF was used as an integral component of ternary binder blends was also tested. The objective was to highlight an optimum proportioning method for CSF concrete in terms of concrete durability. Control series to which the performance of CSF concrete was compared included both PC and binary PC/GGBS mixes.

1. Materials, mix proportioning and curing

Class CEM I, 42,5 PC conforming to SABS ENV 197-1 (1995), silica fume of densified powder form (approximate bulk density 650 kg/m^3), and GGBS conforming to SABS 1491: Part 1 (1989) were used throughout the experimental program. All materials were obtained in single, bulk deliveries and stored in airtight drums to prevent deterioration with time. The coarse aggregate used was crushed greywacke rock of 19-mm nominal maximum size. The fine aggregate used was a washed, pit-sourced material that was continuously graded, relatively coarse, and contained fairly angular, rough-textured particles. Both aggregates met the requirements of SABS 1083 (1979).

The concrete mix proportions used are given in Table 1. Binder combinations considered were as follows:

1. PC control mixes
2. PC/50% GGBS control mixes
3. PC/5% CSF mixes
4. PC/10% CSF mixes
5. PC + 10% CSF mixes
6. PC/40% GGBS/10% CSF mixes

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Table 1
Mix proportions used for experimental study

Constituent materials (kg/m^3)									
Binder					Aggregate				
PC	CSF	GGBS	Total	Water	Fine	Coarse	W/B ratio[a]	Super plasticiser dosage[b]	28-day cube strength (MPa)[c]
(1) PC control mixes[d]									
265	–	–	265	175	923	1040	0.66	–	31.0
315	–	–	315	175	880	1040	0.56	–	39.0
360	–	–	360	175	842	1040	0.49	0.15	51.0
(2) PC/50% GGBS control mixes									
132.5	–	132.5	265	175	913	1040	0.66	–	29.0
157.5	–	157.5	315	175	869	1040	0.56	–	37.0
180	–	180	360	175	829	1040	0.49	–	46.0
(3) PC/5% CSF mixes									
252	13	–	265	175	917	1040	0.66	0.30	38.0
300	15	–	315	175	874	1040	0.56	0.45	48.5
342	18	–	360	175	835	1040	0.49	0.55	55.0
(4) PC/10% CSF mixes									
238	27	–	265	175	911	1040	0.66	0.55	44.5
283	32	–	315	175	867	1040	0.56	0.70	57.0
324	36	–	360	175	827	1040	0.49	0.95	64.0
(5) PC + 10% CSF mixes (i.e., % by addition)									
265	25	–	290	175	891	1040	0.60	0.80	56.0
315	30	–	345	175	843	1040	0.50	1.00	67.0
360	35	–	395	175	798	1040	0.44	1.25	75.0
(6) PC/GGBS/CSF (50/40/10%) mixes									
105	25	135	265	175	902	1040	0.66	0.10	37.0
125	30	160	315	175	856	1040	0.56	0.25	48.0
145	35	180	360	175	815	1040	0.49	0.30	53.0

[a] Water/binder (i.e., PC plus additional materials) ratio.
[b] Dosages given as percent of total binder content by mass.
[c] Results obtained for standard water cured (20°C) specimens (100-mm cubes).
[d] Mixes designed for 28-day strengths of 30, 40, and 50 MPa, respectively.

The PC and PC/GGBS mixes were used as controls, with the latter combination chosen due to its proven ability to provide high levels of concrete durability [4,5]. Based on strength results obtained from an earlier section of the study [6], mix proportions were chosen to achieve 28-day strengths of 30, 40, and 50 MPa for the PC concretes. The water/binder ratios and coarse aggregate contents established for these mixes were then fixed and used throughout for the remaining binder combinations. Fine aggregate contents were adjusted in each case to achieve unit volume.

Binder combinations 3 and 4 used CSF as a replacement material for PC. Alternatively, CSF was used as a direct addition to the original PC content in binder combination 5. Clearly for these mixes the water/binder ratio was altered slightly in comparison to other binder combinations (see Table 1). The final binder combination used a ternary binder blend of PC/GGBS/CSF at the proportions 50/40/10% by mass of binder. These mixes were included due to their potential for providing high levels of concrete durability [7].

Concrete specimens were stored for (a) 28 days in water, 20°C ("wet-curing" regime) and (b) 3 days in water, 20°C and 25 days in air, 20°C, 55% relative humidity ("dry-curing" regime). Concrete specimens prepared using binder combinations 5 and 6 were subjected to the wet-curing regime only.

2. Strength development

Concrete specimens (100-mm cubes) were tested for compressive strength after 28 days of standard water curing and the results are given in Table 1. Clearly the use of varying binder combinations influenced concrete strength development, with increasing dosages of CSF resulting in improved 28-day results. Considering the 0.56 water/binder ratio concretes only (for comparative purposes and as the other water/binder ratio mixes follow very similar trends), 28-day strength increased from 39.0 MPa for the control PC mix to 48.0 and 57.0 MPa for mixes with CSF replacements of 5 and 10% by mass, respectively. When CSF was used as a 10% addition to the binder, strength increased further to 67.0 MPa.

Due to a higher replacement level used and its inherent slower rate of hydration, a slight reduction in strength occurred for the PC/GGBS controls (i.e., 37.0 MPa for the

0.56 water/binder ratio mix). Comparing these results to those for the ternary binder mixes, it is interesting to note that by replacing 10% by mass of GGBS with CSF, the 28-day strength increased to 48.0 MPa. Indeed, the strength results obtained for the ternary binder mixes were almost identical to those for the PC/5% CSF mixes.

3. Durability index tests

Potential concrete durability may be inferred by measuring the resistance of the cover layer to transport mechanisms such as permeation, absorption, and diffusion [8]. Three durability index tests (namely oxygen permeability, water sorptivity, and chloride conductivity tests) have been developed to produce reliable results using simple and inexpensive test methods [8]. These index tests may be defined as techniques that measure the early-age resistance of concrete to the transport of fluids and ions through cover concrete, which ultimately affects deterioration [8]. The purpose of the tests is not to determine absolute or intrinsic material characteristics but to produce reliable index values to be used for comparative purposes. All index results obtained for the wet-cured specimens are given in Table 2. Included in Table 2 are ranges of index values that have been related to estimated "excellent," "good," "poor," and "very poor" concrete performance. These index ranges have been extracted from an earlier study [9] and modified slightly based on practical experience.

3.1. Oxygen permeability index test

Permeability encompasses the transport of liquid, gas, and vapour phases through concrete and is one of the most critical parameters controlling potential durability. This test method uses a falling-head permeameter [10], which measures pressure decay with time as oxygen permeates through concrete. A typical test takes approximately 2–5 h. Specimens (68-mm diameter, 25-mm thick discs) were oven dried (50°C, 15% relative humidity) for 7 days or until constant mass was achieved. From the pressure decay measured, Darcy coefficient of permeability was then determined. The test output is referred to as an oxygen permeability index (OPI), which is defined as the negative logarithm of the coefficient of permeability.

Clearly the use of varying binder combinations significantly affected OPI. Comparing between the 0.56 water/binder ratio mixes only (for simplicity and as the other water/binder ratio mixes follow similar trends), CSF replacements of 5 and 10% by mass increased OPI from 9.97 for the control PC mix to 10.28 and 10.42, respectively, on a log scale. The implication of a reduced OPI for the 10% ad-

Table 2
Durability index test results obtained for wet-cured test specimens

Index test	Estimate of concrete performance [9]			
	Excellent	Good	Poor	Very poor
Oxygen permeability index range	>10.0	9.5–10.0	9.0–9.5	<9.0
Water sorptivity range (mm/√h)	<6.0	6.0–10.0	10.0–15.0	>15.0
Chloride conductivity range (mS/cm)	<0.75	0.75–1.5	1.5–2.5	>2.5
Binder combination	**Durability index test results**			
	Oxygen permeability index	Water sorptivity (mm/√h)	Chloride conductivity (mS/cm)	
(1) Water/binder ratio = 0.66				
PC control	9.71	7.60	2.22	
PC/50% GGBS	9.25	6.24	2.15	
PC/5% CSF	10.03	5.71	1.22	
PC/10% CSF	10.19	4.84	0.91	
PC + 10% CSF (w/b = 0.60)	10.30	3.95	0.63	
PC/40% GGBS/10% CSF	9.62	5.00	0.52	
(2) Water/binder ratio = 0.56				
PC control	9.97	7.08	1.93	
PC/50% GGBS	9.56	5.85	0.81	
PC/5% CSF	10.28	5.10	0.95	
PC/10% CSF	10.42	4.27	0.68	
PC + 10% CSF (w/b = 0.50)	10.34	3.42	0.50	
PC/40% GGBS/10% CSF	9.87	4.41	0.36	
(3) Water/binder ratio = 0.49				
PC control	10.03	5.58	1.49	
PC/50% GGBS	9.69	5.07	0.63	
PC/5% CSF	10.36	4.45	0.81	
PC/10% CSF	10.43	4.13	0.62	
PC + 10% CSF (w/b = 0.44)	10.34	3.44	0.48	
PC/40% GGBS/10% CSF	10.00	4.15	0.31	

dition by mass of CSF mix (10.34) is insignificant due to a suspected low sensitivity of the test to values greater than 10.30. Such OPI values have been estimated to indicate excellent concrete performance [9]. Indeed, excellent concrete performance was achieved by all CSF mixes considered, whereas only at a water/binder ratio of 0.49 did the PC control reach this estimated level of performance. The PC and all of the CSF mixes out-performed the PC/GGBS control, for which an OPI of 9.56 was recorded. This reduced performance is probably related to the maturity of these mixes at the time of testing and represents good concrete performance [9]. Encouragingly, the 10% replacement of GGBS with CSF to form a ternary blended binder resulted in an OPI increase to 9.87. The ternary mixes were, however, out-performed by the control PC and binary CSF mixes in this test.

3.2. Water sorptivity index test

The dominant mechanism controlling rates of water ingress into unsaturated or partially saturated concrete is absorption, caused by the capillary action of concrete's pore structure. Sorptivity is defined as the rate of movement of a waterfront through a porous material under capillary action [11]. Test specimens from the oxygen permeability test were reused in this test after being reconditioned in an oven overnight (50°C, 15% relative humidity). Layers of absorbent material were saturated in a plastic tray with a distilled water/$Ca(OH)_2$ solution. By periodically placing samples onto the saturated material, the rate of absorption was then monitored using an electronic balance. Sealing the sides of the test discs ensured uniaxial absorption.

Water sorptivity results were also significantly influenced by the binder combination used. Again considering the 0.56 water/binder ratio mixes only, a value of 7.08 mm/√h was initially recorded for the PC control mix. In comparison to the OPI results, water sorptivity was markedly improved through the use of a 50% GGBS replacement and a value of 5.85 mm/√h was noted for this mix. Performance was further improved through the use of CSF. CSF replacements of 5 and 10% by mass resulted in water sorptivity index values of 5.10 and 4.27 mm/√h, respectively. A 10% addition of CSF by mass of the binder content caused the greatest improvement in performance, with an index of 3.42 mm/√h obtained. Index values less than 6.0 mm/√h have been reported to represent excellent concrete performance [9]. The index values obtained for the ternary blended binder mixes were lower than those obtained for the PC and PC/GGBS controls and ranked between the 5 and 10% CSF replacement mixes in terms of performance. This trend again demonstrates the beneficial effects of CSF and its suitability for use in conjunction with GGBS.

3.3. Chloride conductivity test

Resistance to chloride ion penetration is pivotal to the durability of structures exposed to marine or deicing salt conditions. The chloride conductivity test involves determining the DC conductivity of concrete samples (68-mm diameter, 25-mm thick discs) saturated with a 5 M NaCl solution [12]. To achieve NaCl saturation, samples were preconditioned prior to testing by oven drying (50°C, 15% relative humidity) for 7 days, followed by 24 h of vacuum saturation in a 5 M NaCl solution. A 10-V potential difference was then applied across the ends of each specimen, using a conduction cell filled with a 5 M NaCl solution. The electrical current passing through each specimen was measured, and conductivity was determined from the specimen dimensions and the specimen electrical resistance.

The chloride conductivity of concrete was significantly affected by the binder combination used, with CSF causing marked index reductions. Comparing the 0.56 water/binder ratio mixes only, those with 5 and 10% CSF replacements by mass reduced the index result of 1.93 mS/cm obtained for the control PC to 0.95 and 0.68 mS/cm respectively. The performance of the PC/GGBS control ranked between these two CSF concretes with an index value of 0.81 mS/cm recorded. Chloride conductivity was further reduced when CSF was used as an addition to the binder content. The ternary blended binder mixes, however, achieved optimum performance. Index values for these 0.56 water/binder ratio mixes were 0.50 and 0.36 mS/cm, respectively. From Table 2 it can be seen that the PC controls generally achieved poor concrete performance. Both the PC/GGBS controls and the CSF mixes ranged in performance from poor to excellent, with improvements occurring with reduction of water/binder ratio. This trend was to be compared to the ternary blended binder mixes, where excellent performance was achieved for all mixes.

4. Influence of curing regime

Overall, and in comparison to the results given in Table 2, the effect of the dry-curing environment was detrimental to performance. Average changes in index results (representing reduced performance) over the range of water/binder ratios considered are given in Fig. 1. The PC/GGBS mixes proved to be the most sensitive to a lack of moist curing, with maximum changes in index results noted for these mixes. On the other hand, CSF concrete appeared to be the least sensitive to a lack of moist curing. This trend became increasingly marked at higher CSF dosages with the lowest changes in index values noted for the PC/10% CSF mixes.

Due to the practical problems and economic implications associated with applying effective curing regimes, the lower sensitivity of CSF concrete to a lack of moist curing, as evident from this study, is clearly of significance. It is realised, however, that due to silica fume's rapid reactivity, in comparison to GGBS, the 3 days of standard wet curing received by the dry-cured specimens may have allowed these mixes to mature to a much greater extent. For this reason, further work in this area is merited in order to investigate the sensitivity of silica fume concrete performance to increasingly harsh curing environments.

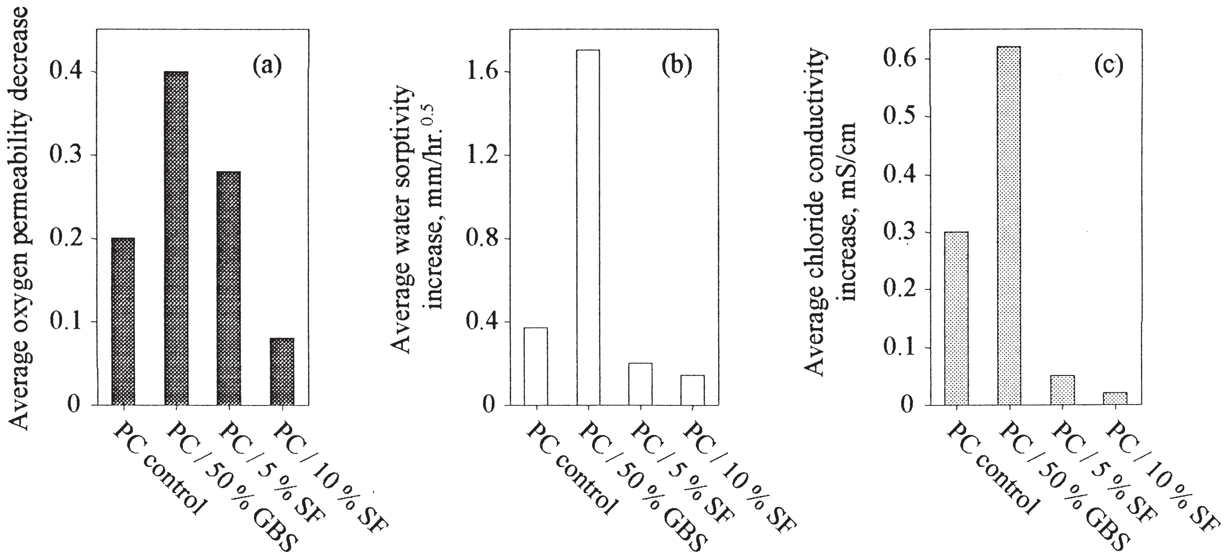

Fig. 1. Influence on index results of replacing wet-curing regime with dry-curing regime.

5. Discussion

The overall durability of concrete is likely to be markedly improved through the use of CSF. By first ranking the performance of each binder combination in the three index tests, then totalling these numbers and ranking again, each binder type may be listed in descending order of performance as follows:

1. PC + 10% CSF mixes
2. PC/10% CSF mixes
3. PC/40% GGBS/10% CSF mixes
4. PC/5% CSF mixes
5. PC/50% GGBS control mixes
6. PC control mixes

In practice, factors such as mix economy may dictate whether CSF is used as a PC addition or replacement. This study clearly shows that the greatest improvements in durability were achieved through its use as a 10% addition by mass to the PC content. This improvement in durability was in addition to maximum 28-day strength development noted for these mixes. In terms of life cycle cost of concrete structures, benefits of using CSF concrete are likely to justify any increase in initial mix cost.

This work also highlights the evident compatibility of GGBS and CSF for use in ternary blended binders. Indeed, these mixes were found to out-perform both the controls and PC/5% CSF mixes. As testing was carried out after 28 days, further improvements in performance with age may be expected for these mixes due to continuing GGBS reactivity, providing sufficient moist curing is available. Further research is certainly merited to quantify the performance of such concrete in exposures where the availability of moisture is limited. In terms of chloride resistance, the inherent limited chloride-binding capability of binary CSF mixes [13] may additionally be overcome through blending with GGBS. In this way the considerable microstructural benefits offered by CSF may be complimented with the binding capacity of GGBS in order to optimise chloride resistance.

6. Conclusions

1. Maximum strength development was recorded for PC + 10% CSF by mass mixes. The lowest strengths were achieved by the PC/GGBS controls. Performance of these mixes was markedly improved, however, when CSF replaced 10% by mass of the total binder forming a ternary blend.
2. Durability index tests indicated that performance was significantly improved when using CSF. Within the range of mixes considered, the PC + 10% CSF mixes achieved optimum performance.
3. High levels of durability performance are achievable by using ternary blends of PC/GGBS/CSF. In this study these mixes out-performed the PC, PC/GGBS, and PC/5% CSF mixes. As testing was carried out at 28 days, longer-term improvements in performance are likely for these mixes.
4. Durability performance of all concrete mixes was reduced when the dry-curing regime replaced the wet-curing regime. CSF mixes were least sensitive to lack of moist curing, however, with the lowest changes in durability index results noted for these mixes.

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References

[1] M. Lachemi, G. Li, A. Tagnit-Hamou, P.-C. Aitcin, Long-term performance of silica fume concretes, Concr Int 20(1) (1998) 59.
[2] J. Bijen, Benefits of slag and fly ash, Construction & Building Materials, 10 (1996) 5.
[3] V.M. Malhotra, Fly ash, slag, silica fume and rice-husk ash in concrete. A review, Concr Int 15 (1993) 4.
[4] Building Research Establishment. Durability of blastfurnace slag cement concretes, BRE Information Paper, IP 6/92, 1992.
[5] M. Connell, Long-term performance of high slag concrete, Concrete (London), 32 (1998) 6.
[6] B.J. Magee, M.G. Alexander, Concrete containing densified silica fume: Fresh properties, strength development, mix design, (in press).
[7] M.R. Jones, R.K. Dhir, B.J. Magee, Conc. containing ternary blended binders: Resistance to chloride ingress and carbonation, Cem Concr Res 27 (1997) 6.
[8] M.G. Alexander, An indexing approach to achieving durability in concrete structures, FIP Symposium, The Concrete Way to Development, Johannesburg, Concr. Soc. of Southern Africa, 1997, pp. 571–576.
[9] M.G. Alexander, J.R. Mackechnie, G.E. Hoppe, Measures to ensure effective curing and concrete durability during construction, Proc. 15th Annual Transportation Convention, Pretoria, 1995.
[10] Y. Ballim, A low cost falling head permeameter for measuring gas permeability, Conc Beton 61 (1991).
[11] M. Kelham, A water absorption test for concrete, Magazine of Concrete Research 40 (1988) 143.
[12] P.E. Streicher, M.G. Alexander, A chloride conduction test for concrete, Cem Concr Res 25 (1995) 6.
[13] P.S. Mangat, B.T. Molloy, Chloride binding in concrete containing PFA, GBS or silica fume under sea water exposure, Mag Concr Res 47 (1995) 171.